2001 Joint GEM-SHINE Workshop
Snowmass, CO, USA
17 June 2001

Relativistic electron dynamics in the inner magnetosphere: Do we know enough for predictions?

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A1. Overview
Introduction

There is intense interest in isolating and understanding the mechanisms that contribute to the frequently observed MeV electron flux buildups in the outer magnetosphere, typically during the recovery phase of geomagnetic storms.

There is increasing evidence of the correlation between the occurrence of these fluxes and of subsequent spacecraft operating anomalies or failures.

Because of the apparent complexity of these mechanisms, their understanding will contribute significantly to the general knowledge of transport and heating processes in the magnetosphere.

The unprecedented density of observations in the modern era has led to new questions. Data from instruments on SAMPEX, Polar (CEPPAD), GPS (BDD-II), CRRES (MEA), LANL Geo (ESP), GOES, and HEO has lead to a revival of relativistic electron research.

A2. Overview
Outline

We review previous observations which have led to the development of several ideas and theories about relativistic electron "acceleration" in the inner magnetosphere.

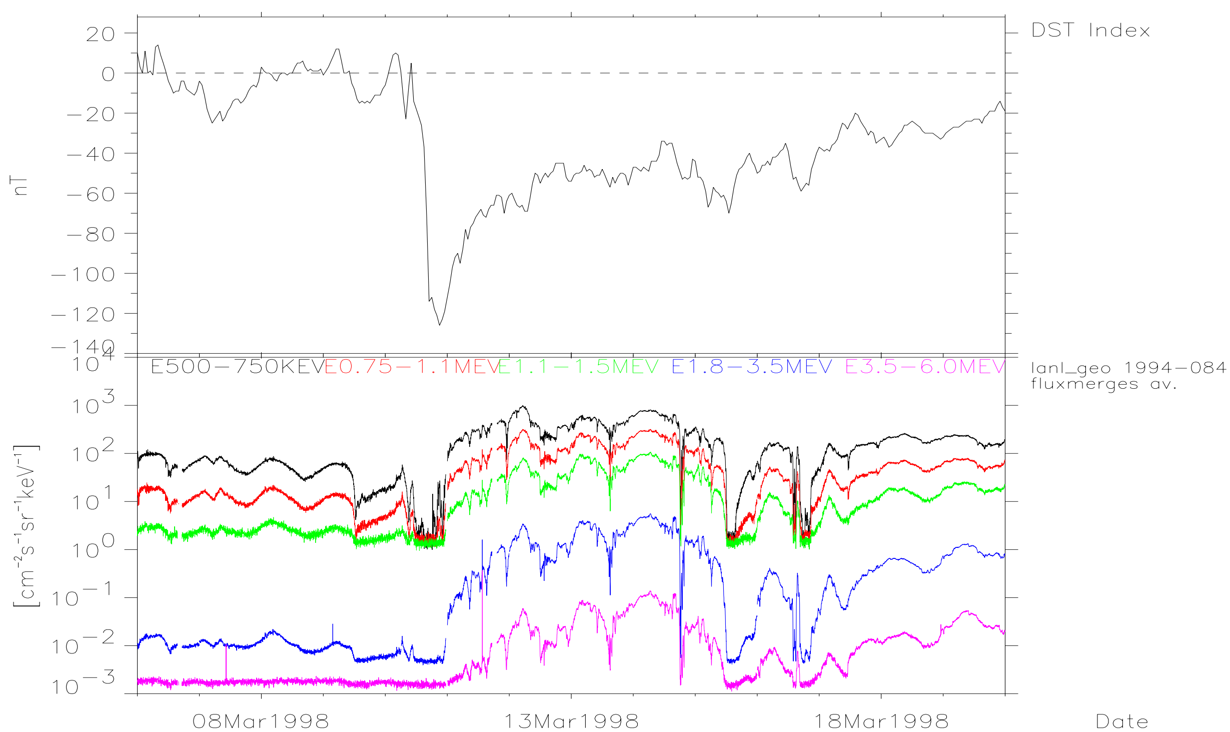
The most prominent theories and ideas are presented and contrasted.

We then present work treating these events relativistic electron buildup events in a statistical manner, trying to establish what the controlling conditions in the solar wind and/or magnetosphere are that lead to geoeffective relativistic electron buildups.

Finally, we will present some recent research into relativistic electron losses.

B1. Observed dynamics: Relativistic electron buildup

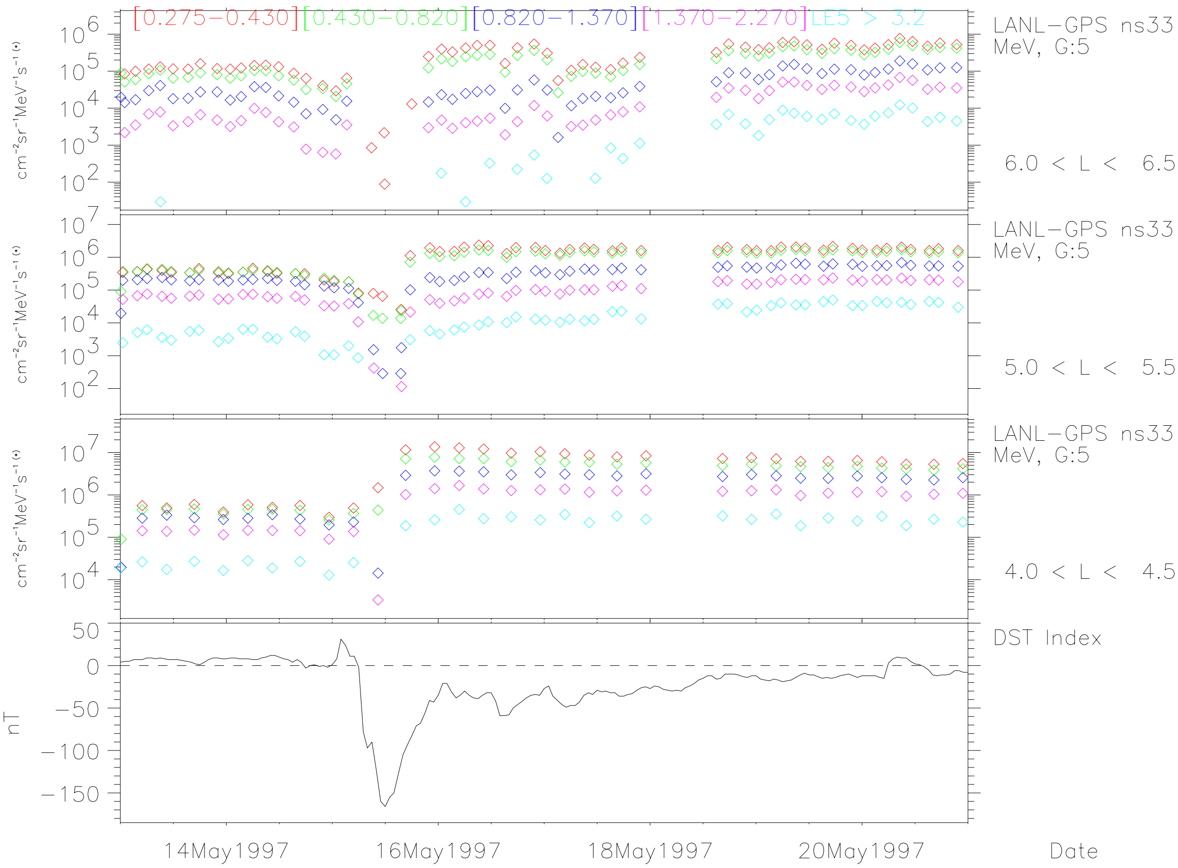
Williams [1966] related periodic increases in the relativistic electrons to increases in the solar wind kinetic energy density. *Paulikas and Blake* [1979] noted the connection between relativistic electron fluxes, magnetic storms and solar wind speed.



1.8–2.5 MeV (blue) increases by over two orders (!) of magnitude 3 days after onset. The delayed response was originally explained by the recirculation model of *Fujimoto and Nishida* [1990].

B2. Observed dynamics: Inner magnetospheric response

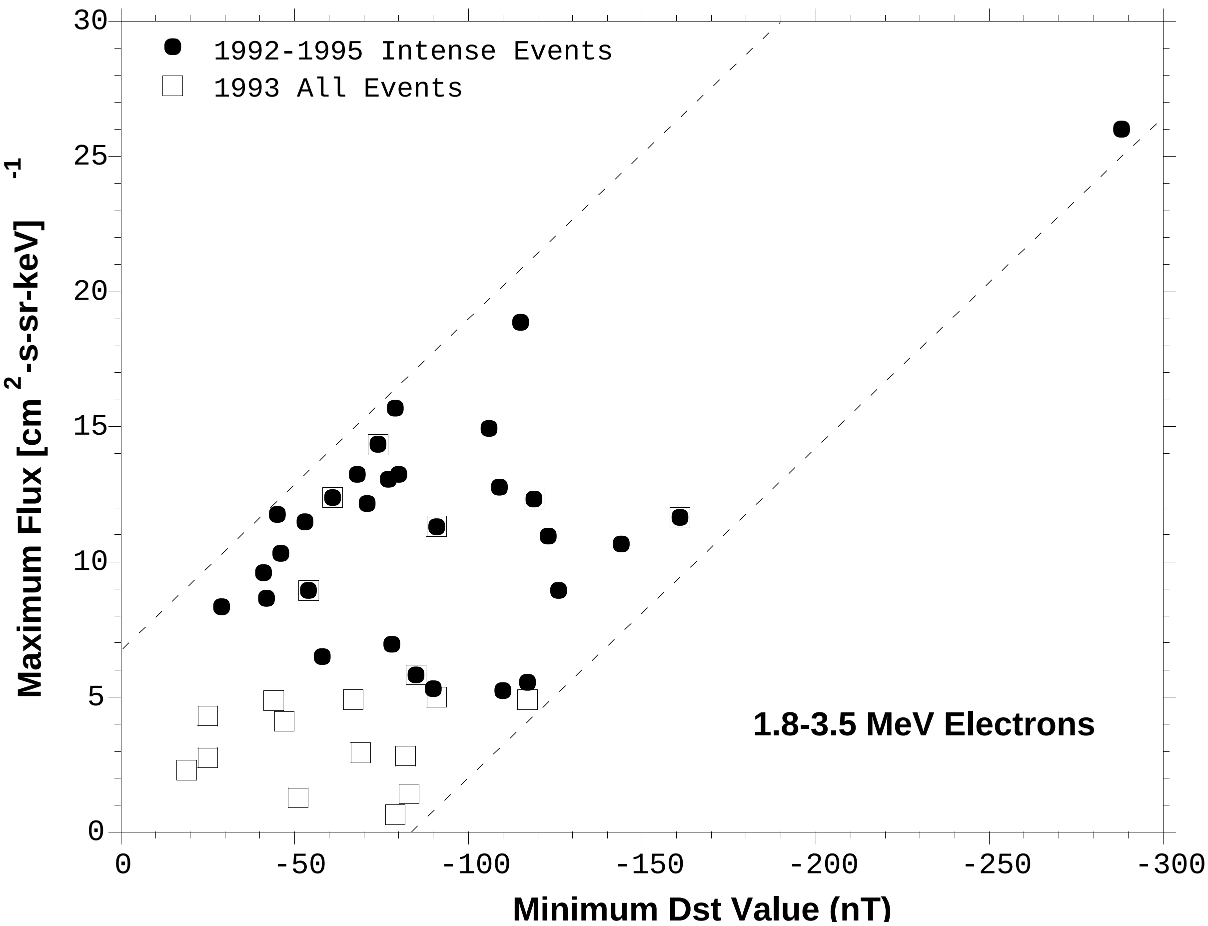
Detailed observations have revealed very fast (< 3 hours) relativistic enhancements deep in the inner magnetosphere which are not consistent with the original recirculation idea, which predicts a much slower rise.



Multiple GPS satellite measurements have shown that this increase at $L = 4$ can occur within three hours or less.

B3. Observed dynamics: Inner magnetospheric response

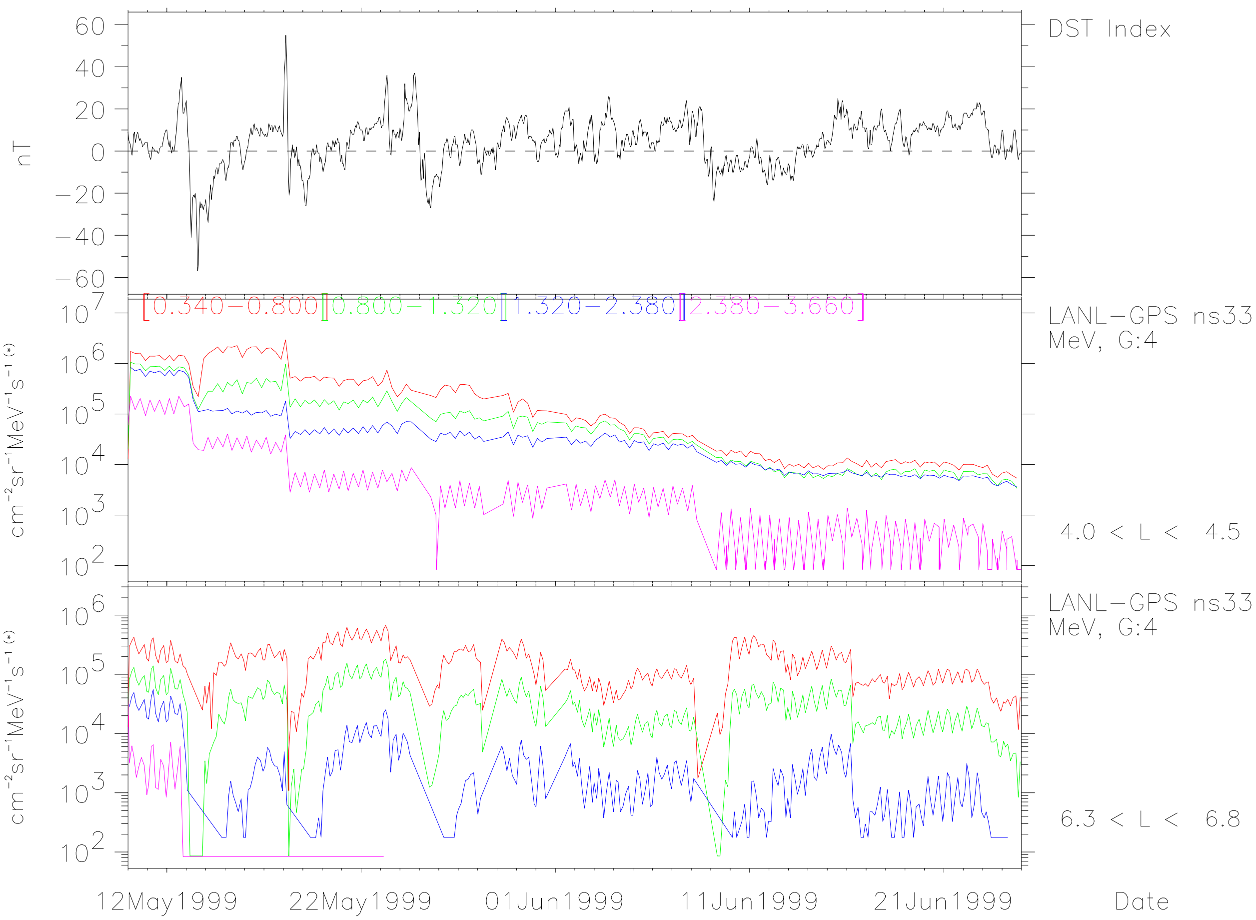
[*Reeves*, 1998] showed that while in general enhancements accompany storms, the magnitude of any given enhancement can vary over a wide range for any given storm strength as measured by Dst.



As one of us has repeatedly stated, "If you've seen one storm, you've seen one storm!".

B4. Observed dynamics: Losses

An intriguing example of losses in the inner magnetosphere is from a very quiet period during May to August 1999.



Stepwise decreases in the relativistic electron channels measured by GPS near $L = 4$ are very clear.

C1. A zoo of mechanisms (a)

1: Large scale recirculation in the magnetosphere involving radial diffusion and pitch angle scattering [*Fujimoto and Nishida*, 1990];

2: Jovian electrons as a source for MeV electrons in the magnetosphere during those times when the interplanetary magnetic field lines connect Jupiter and Earth [*Baker et al.*, 1979, 1986];

3: small scale recirculation in the magnetosphere involving radial diffusion and pitch angle scattering [*Boscher et al.*, 2000; *Liu et al.*, 1999];

4: electron cyclotron heating by whistler waves [*Temerin et al.*, 1994; *Li et al.*, 1997; *Summers et al.*, 1998];

5: adiabatic effects in a storm recovery as the earthward motion of flux surfaces during the Dst decay energizes electrons and ions [*Kim and Chan*, 1997; *McAdams and Reeves*, 2001];

6: enhanced radial transport through interaction with ULF pulsations, which leads to inward transport and adiabatic heating of electrons whose drift frequency satisfies a resonance condition with the pulsation frequency [*Hudson et al.*, 1999; *Elkington et al.*, 1999];

C2. A zoo of mechanisms (b)

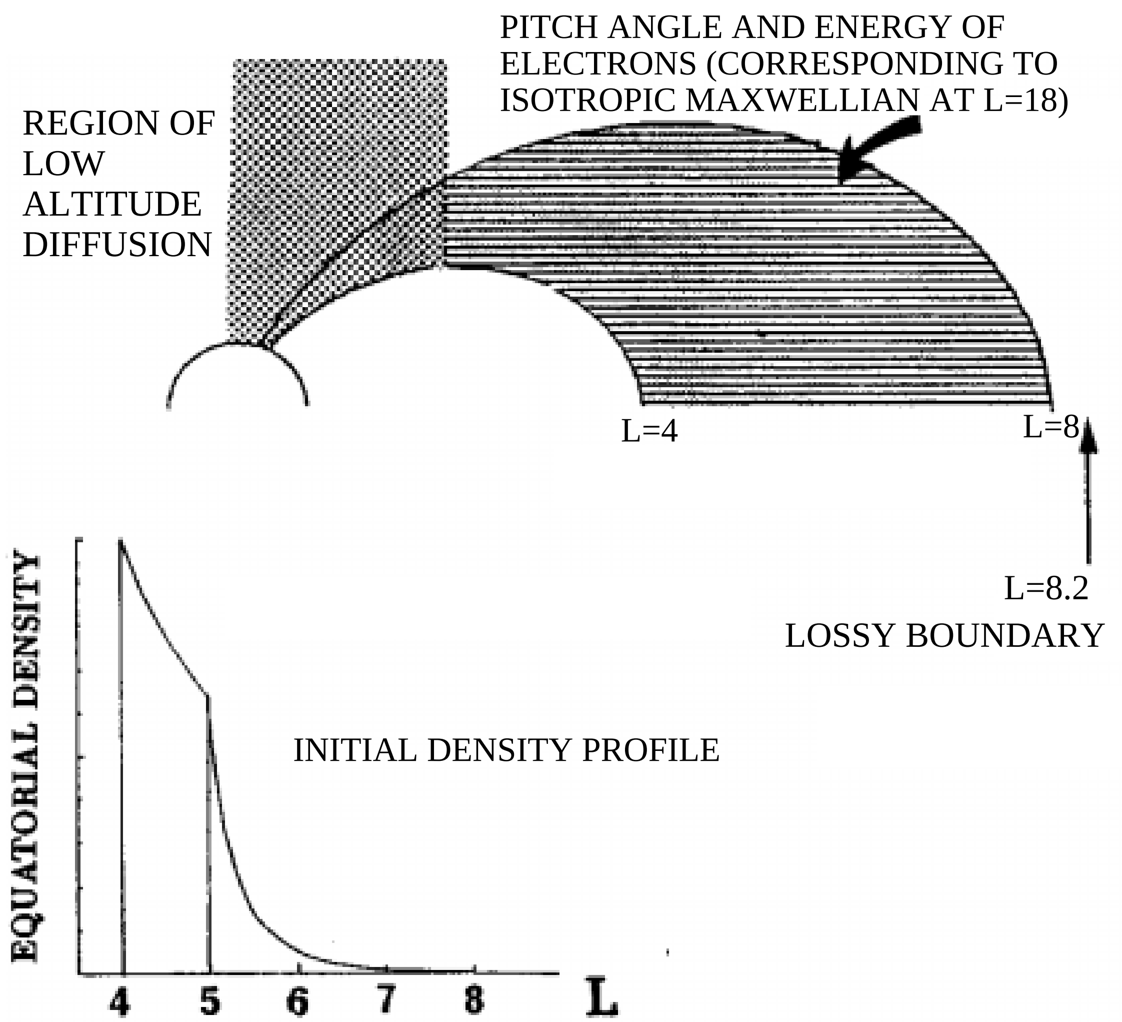
7: diffusion of trapped energetic electrons in the cusp into the radiation belts [*Sheldon et al.*, 1998];

8: enhanced earthward transport from $x \approx -10 R_E$ to geosynchronous altitude of MeV electrons by direct substorm injection [*Ingraham et al.*, 1999, 2000, 2001, accepted]

9: and by enhanced radial diffusion alone [*Hilmer et al.*, 2000; *McAdams et al.*, 2001]. Here the diffusion mechanism is left unspecified, but the authors argue that on the basis of the phase space density gradients observed radial diffusion alone (no recirculation) could account for the observed flux increases.

C3. A zoo of mechanisms
Large Scale recirculation

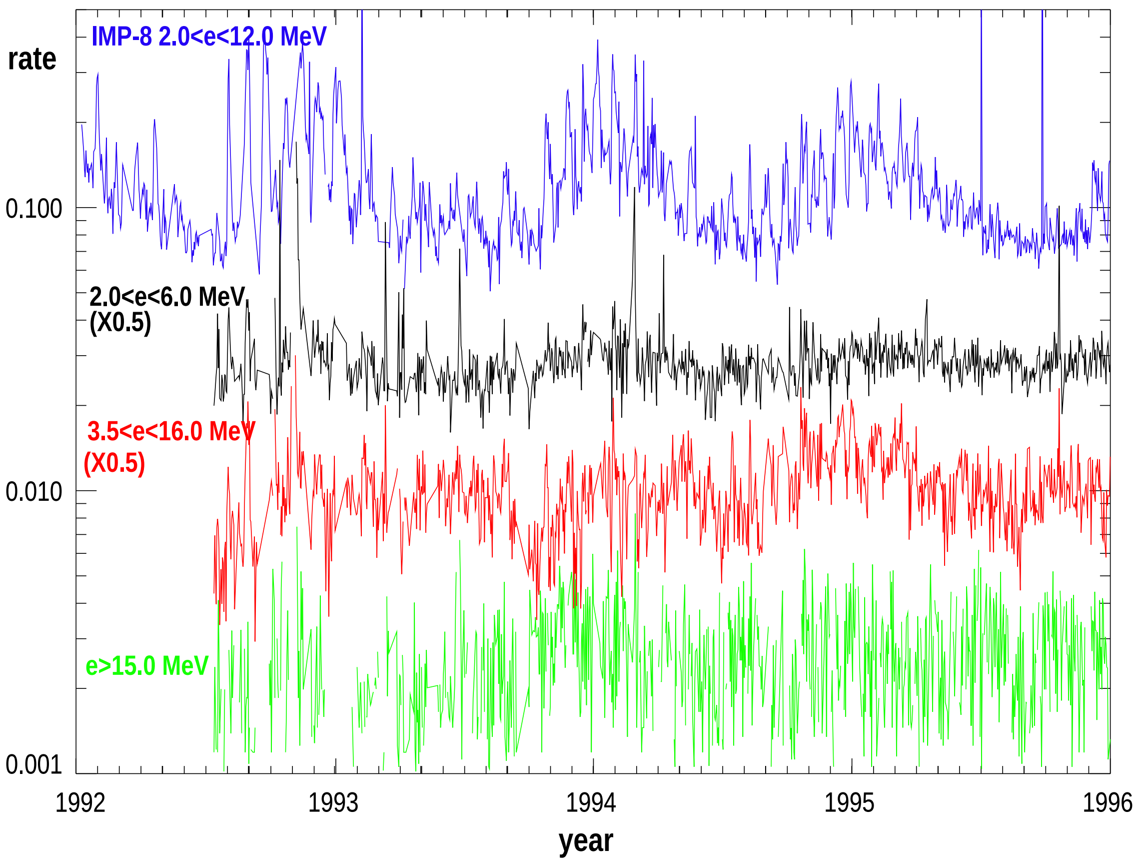
The idea of particle acceleration by multimodal diffusion had been proposed before by several authors [*Roederer*, 1970; *Schulz and Lanzerotti*, 1974].



The main feature of this model [*Fujimoto and Nishida*, 1990] was to combine conventional radial diffusion with the essentially energy preserving cross-L diffusion at low altitudes.

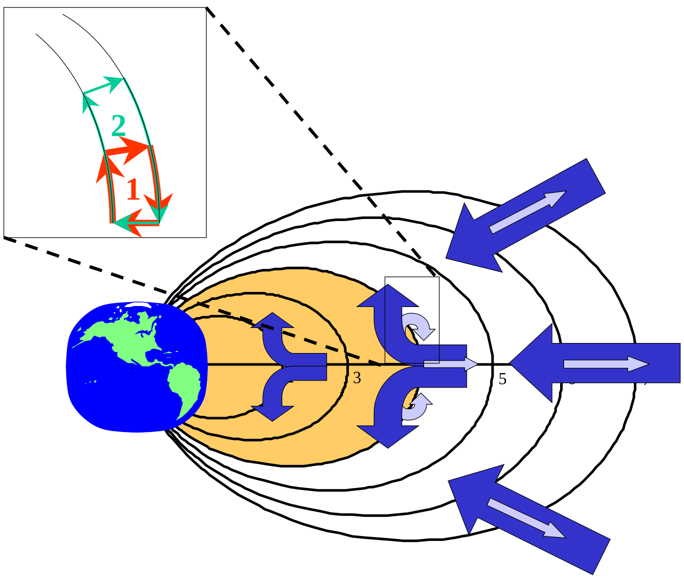
C4. A zoo of mechanisms Jovian Electron Source

Nishida [1976] showed that trapped energetic particles from the Jovian radiation belts can leak into the interplanetary medium.

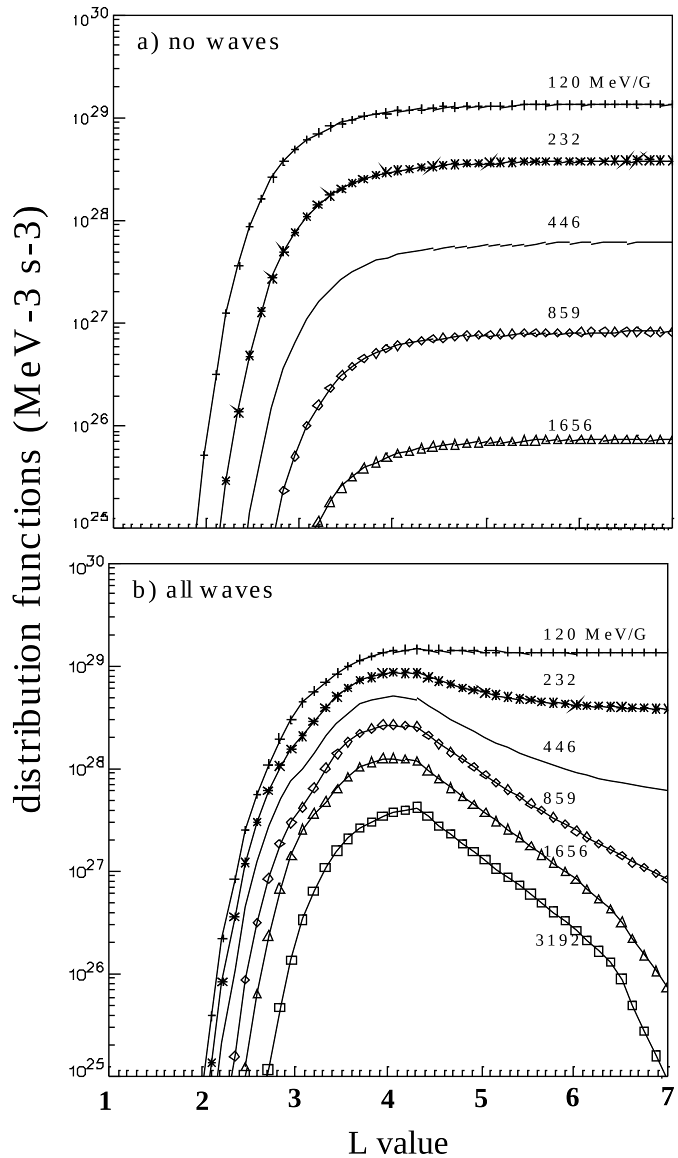


Baker et al. [1979, 1986] then proposed that, during times when the Earth and Jupiter are "connected", these Jovian electrons can enter the terrestrial magnetosphere and could form a source of the observed relativistic electron population.

C5. A zoo of mechanisms The Salammbô model



Localized recirculation near plasmapause, subsequent diffusion to higher *L*. [*Beutier and Boscher*, 1995; *Bourdarie et al.*, 1996; *Boscher et al.*, 2000]



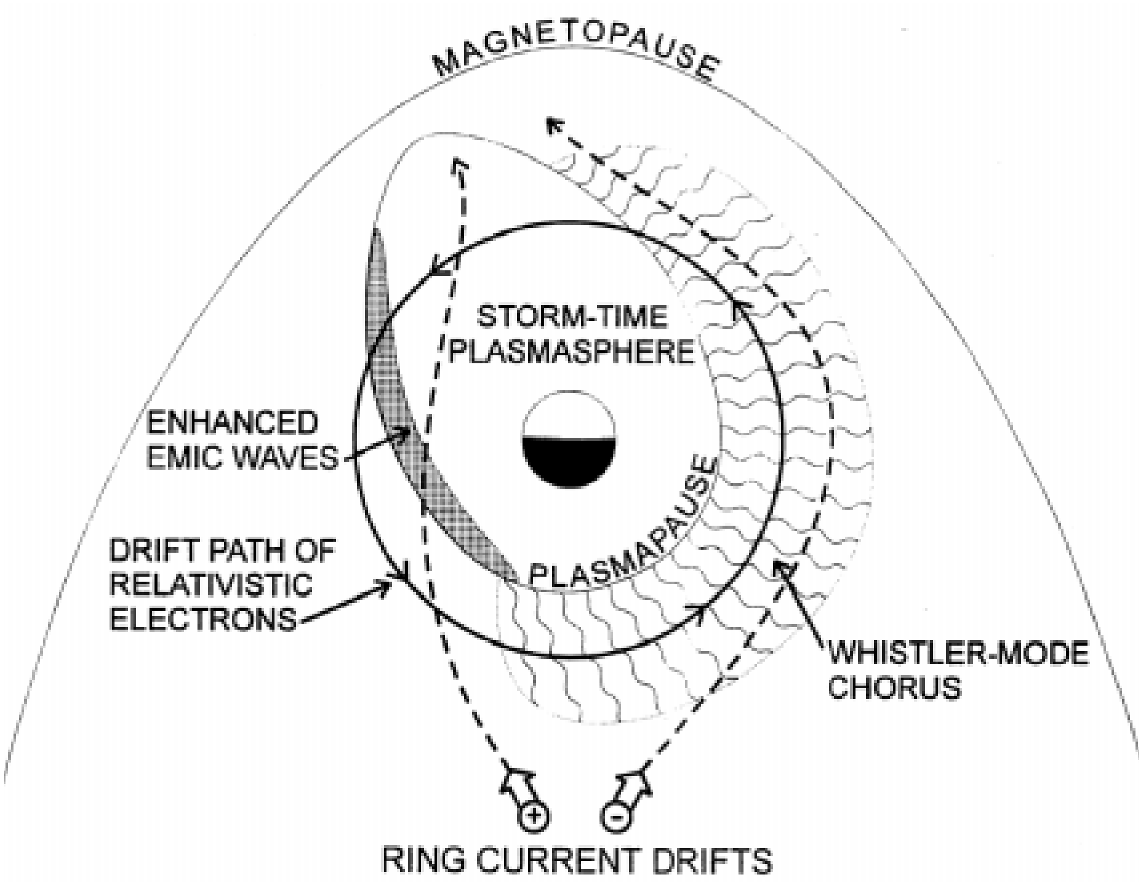
PSD profiles predicted by the code as a function of μ show a clear PSD peak near L=4.

An example of a model run of a magnetic storm will be shown later.

C6. A zoo of mechanisms
Electron cyclotron heating

The Energetic Particle Team at Los Alamos National Laboratory

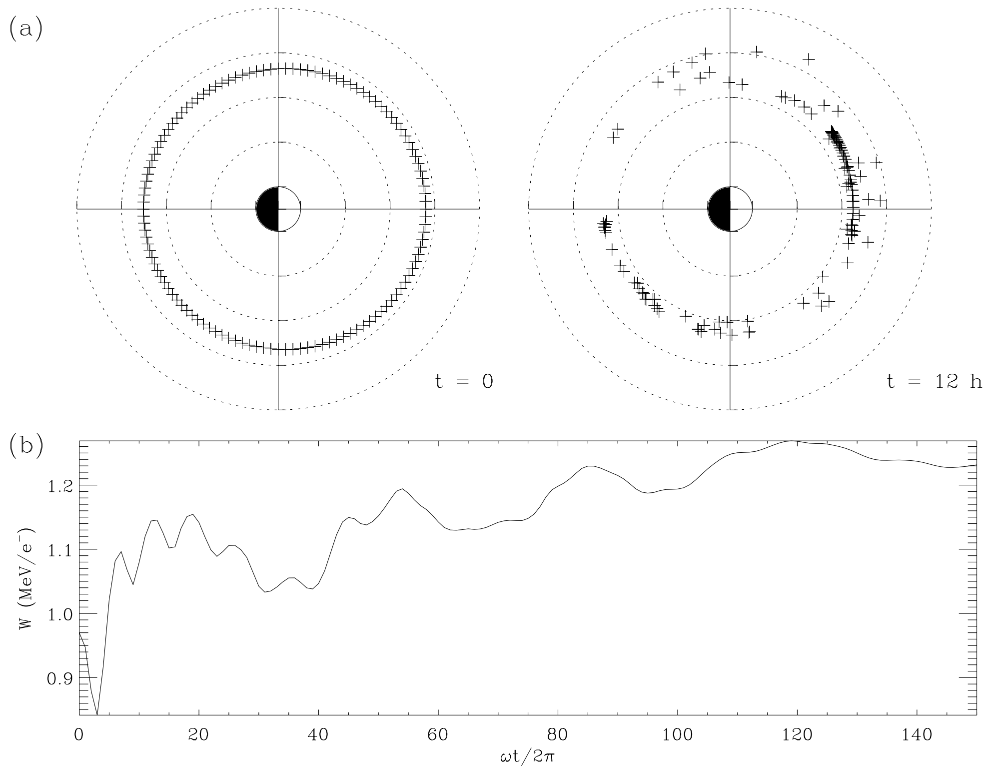
This model is based on diffusion coefficients for gyroresonant electron-whistler mode wave interaction, a source representing substorm-produced (lower-energy) seed electrons, and a loss term representing electron precipitation due to pitch angle scattering by whistler mode and EMIC waves.



In this picture, the wave activity can account for both the loss and subsequent acceleration of relativistic electrons.

C8. A zoo of mechanisms Direct Heating by ULF

Elkington et al. [1999] added convection electric fields to a simulation where the drift period is similar to the ULF period.

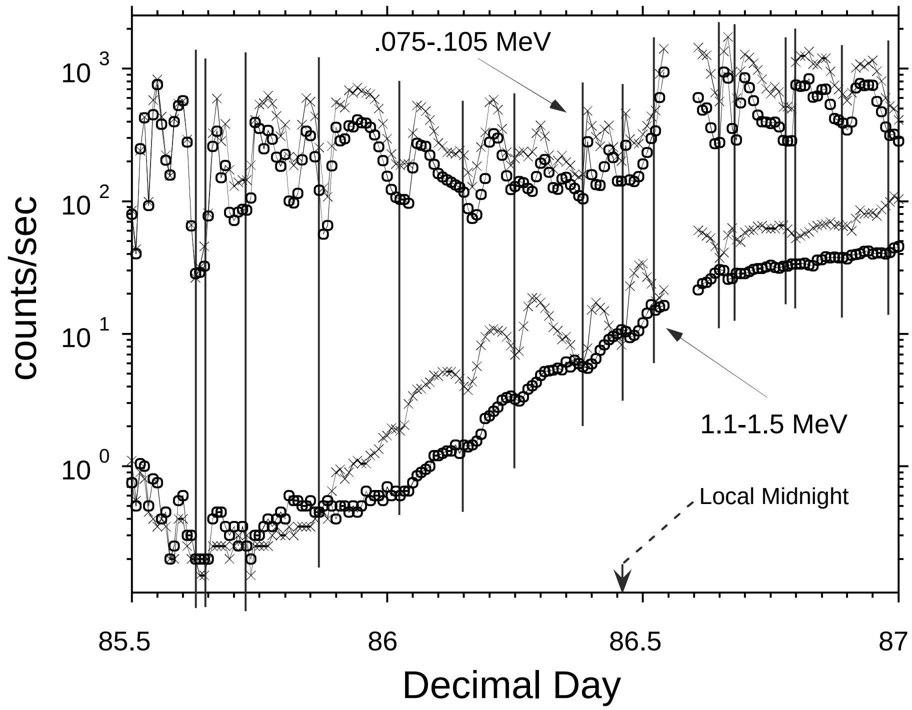


(a) Particle positions for a ring of near-geosynchronous particles moving in a 2 mHz, 3 mV/m toroidal oscillation with an imposed dawn-dusk convection electric field of 5 mV/m. (b) Average particle energy for particles depicted in (a), as a function of wave cycle.

The addition of the convection electric field makes it possible to accelerate particles regardless of their initial phase.

C9. A zoo of mechanisms Substorm Acceleration

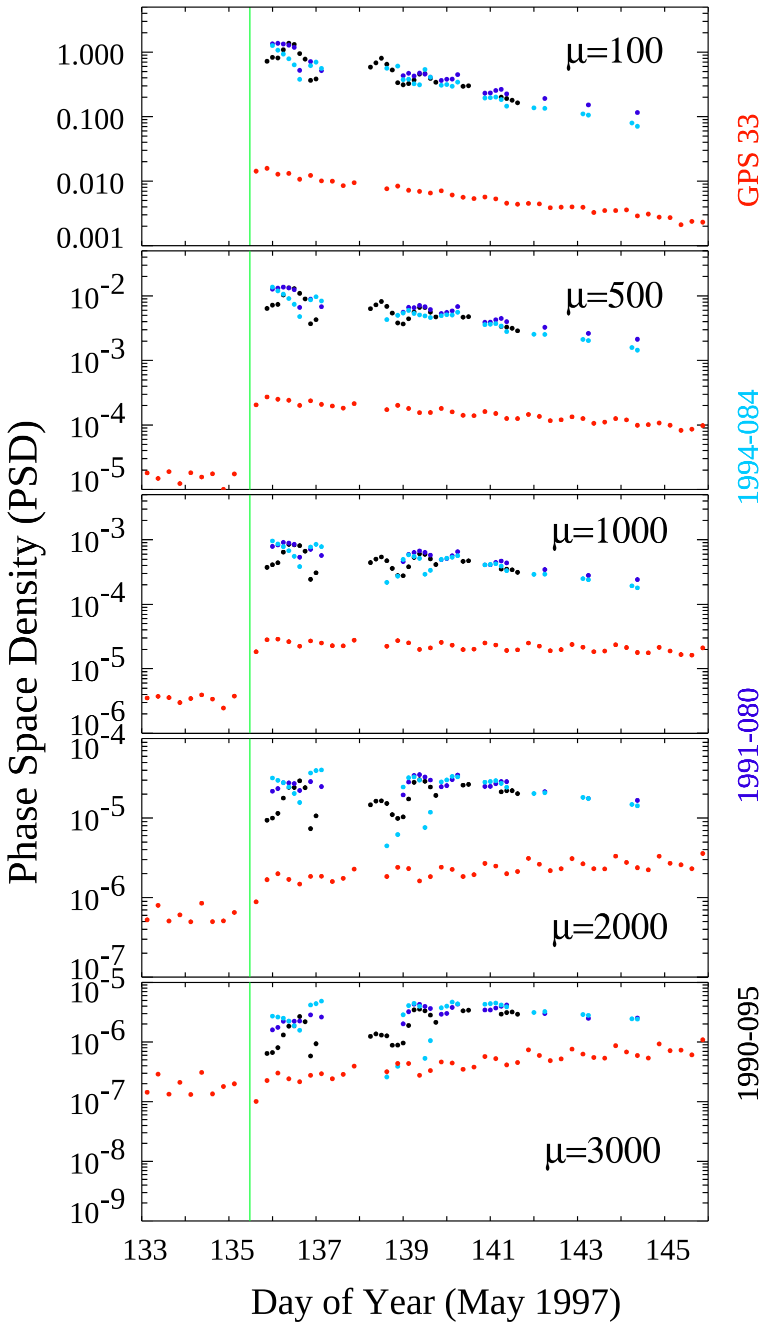
There is evidence that strong, repetitive substorms (such as occurred in the recovery of the March 24, 1991, storm) can directly transport MeV electrons to geosynchronous altitude from $x \approx -10R_E$.



12-minute average pitch angle distribution data for lower-energy (0.075–0.105 MeV) and for higher-energy (1.10–1.50 MeV) electrons from the SOPA on 1989-046. Near-parallel pitch angles (open circles), and near-perpendicular pitch angles (X's). Vertical lines indicate the times of substorm injections as determined from direct measurement, or from a dipolarization measured by a GOES magnetometer. From *Ingraham et al.* [2001, accepted].

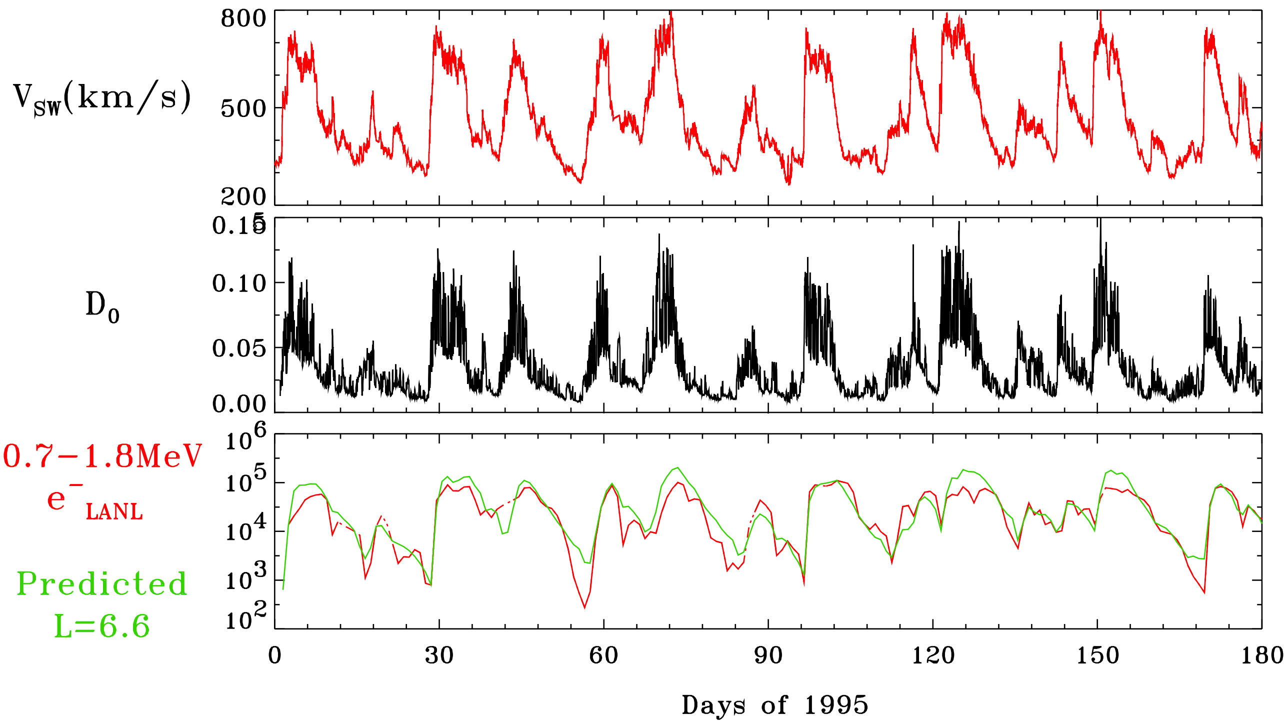
C10. A zoo of mechanisms Enhanced Radial Transport (a)

Hilmer et al. [2000] and *McAdams et al.* [2001] used data from GPS at the equator and LANL geosynchronous satellites. This yields at least two points on the curve of the equatorial PSD. For all the storms examined by these authors (34) the PSD at geosynchronous ($L = 6.6$) was found to be always larger than that at GPS at the equator ($L = 4.2$). The Figure shows the PSD at LANL and GPS for one of the four storms examined by *McAdams et al.* [2001]



C11. A zoo of mechanisms Enhanced Radial Transport (b)

In a recent work *Li et al.* [2001] developed a model to predict MeV electrons at geostationary orbit on the basis of solar wind measurements

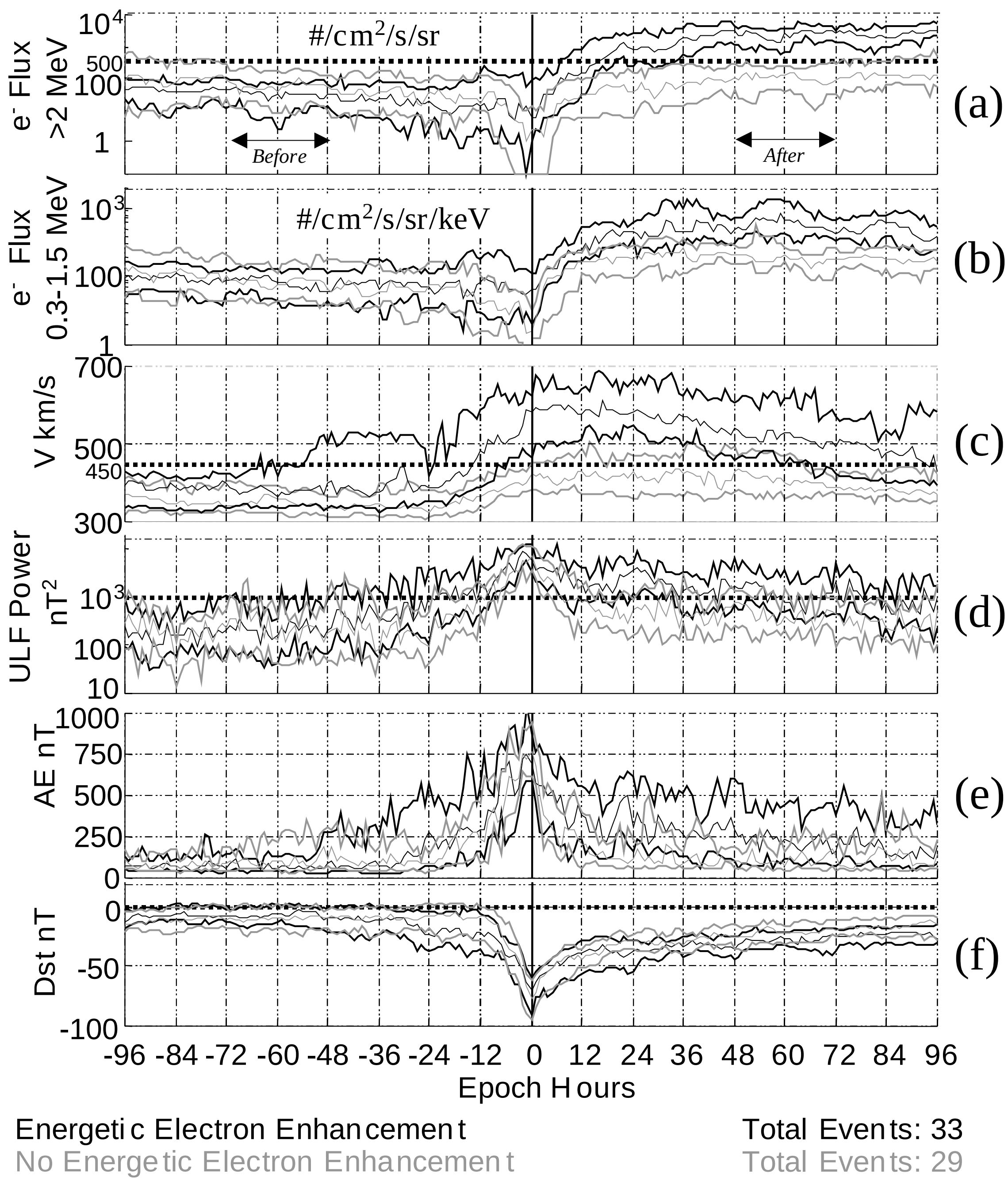


Most relevant solar wind and model parameters and model prediction/data comparison for geostationary relativistic electron fluxes for the first half of 1995.

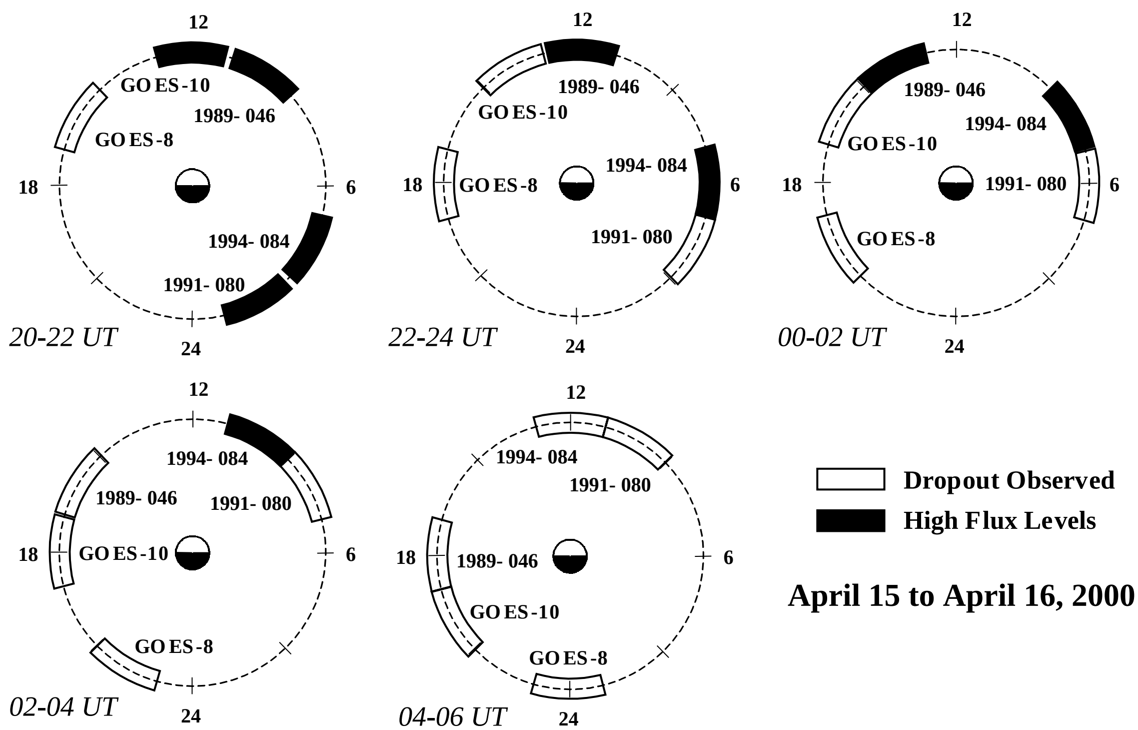
Assumes diffusion-like process and a source at L=11, modulated by solar wind speed fluctuations. Achieves prediction efficiencies of 0.8 or better.

D. Statistical Studies Looking at ALL storms

The most exhaustive statistical study of the geosynchronous response has been performed by *O'Brien et al.* [2001].

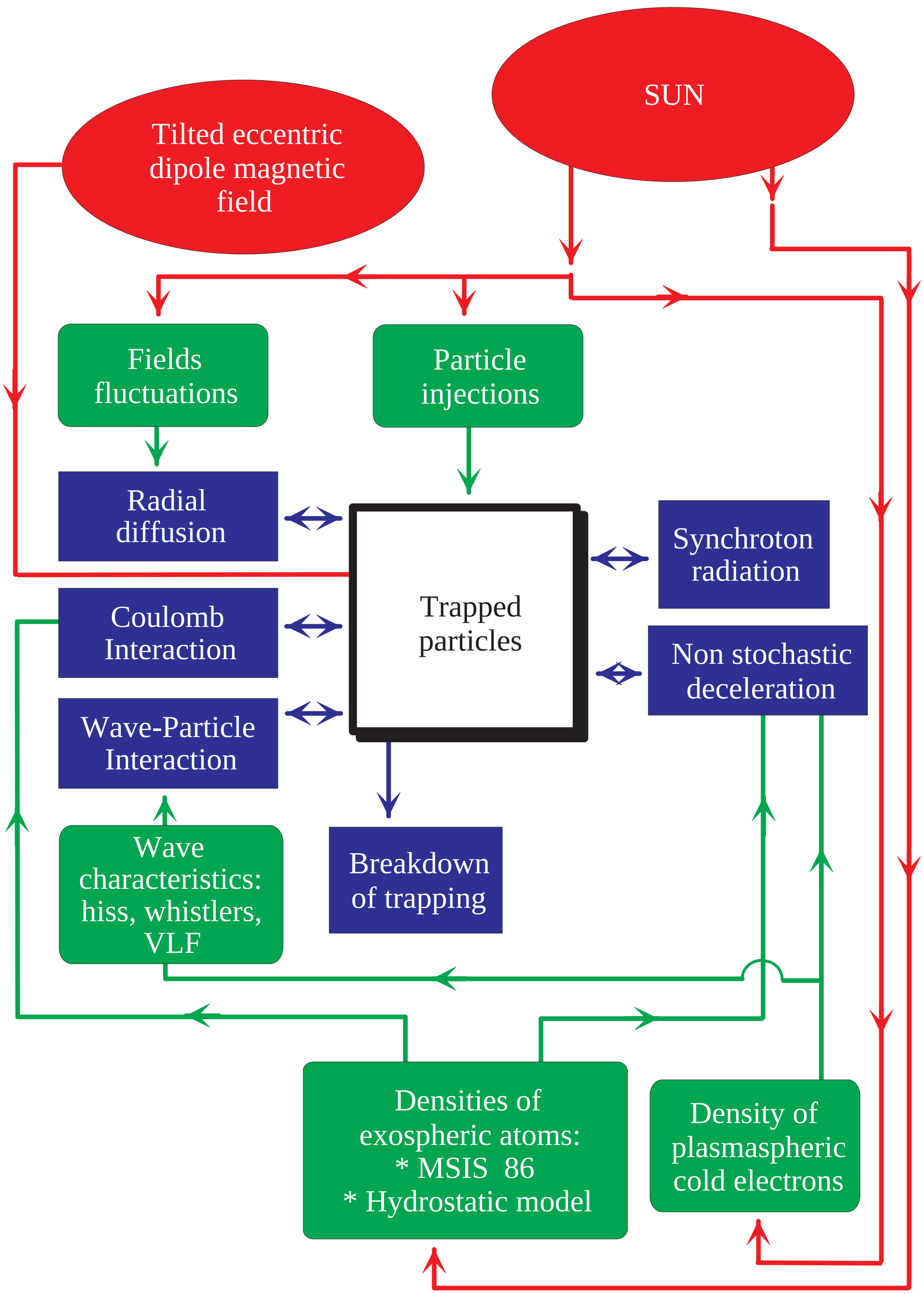


E. Losses



Onsager et al. [2001, submitted] argue that the flux dropouts are due to the development of local, tail-like magnetic field topographies, and not due to more global processes like large-scale radial diffusion. They also showed that lower energy electrons $<$ 300 keV recover fully while the $>$ 2 MeV electrons can be permanently lost. This indicates that there is an energy-dependent non-adiabatic process that acted to remove these electrons from the trapping region.

F1. Salammbô block diagram

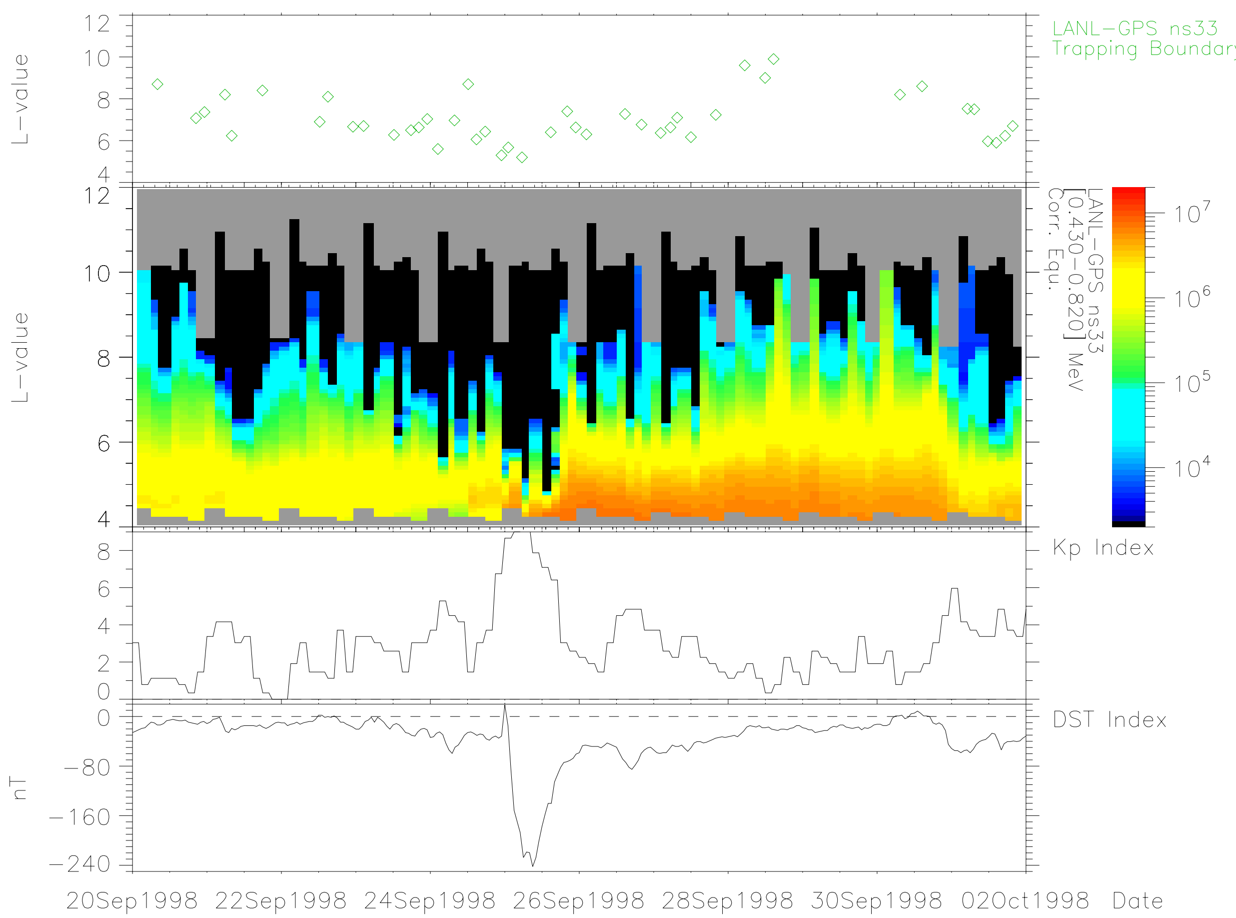


F2.

GPS Satellites
Loss measurements

Detect steep radial gradients in GPS passes through radiation belts. Several strict conditions have to be met:

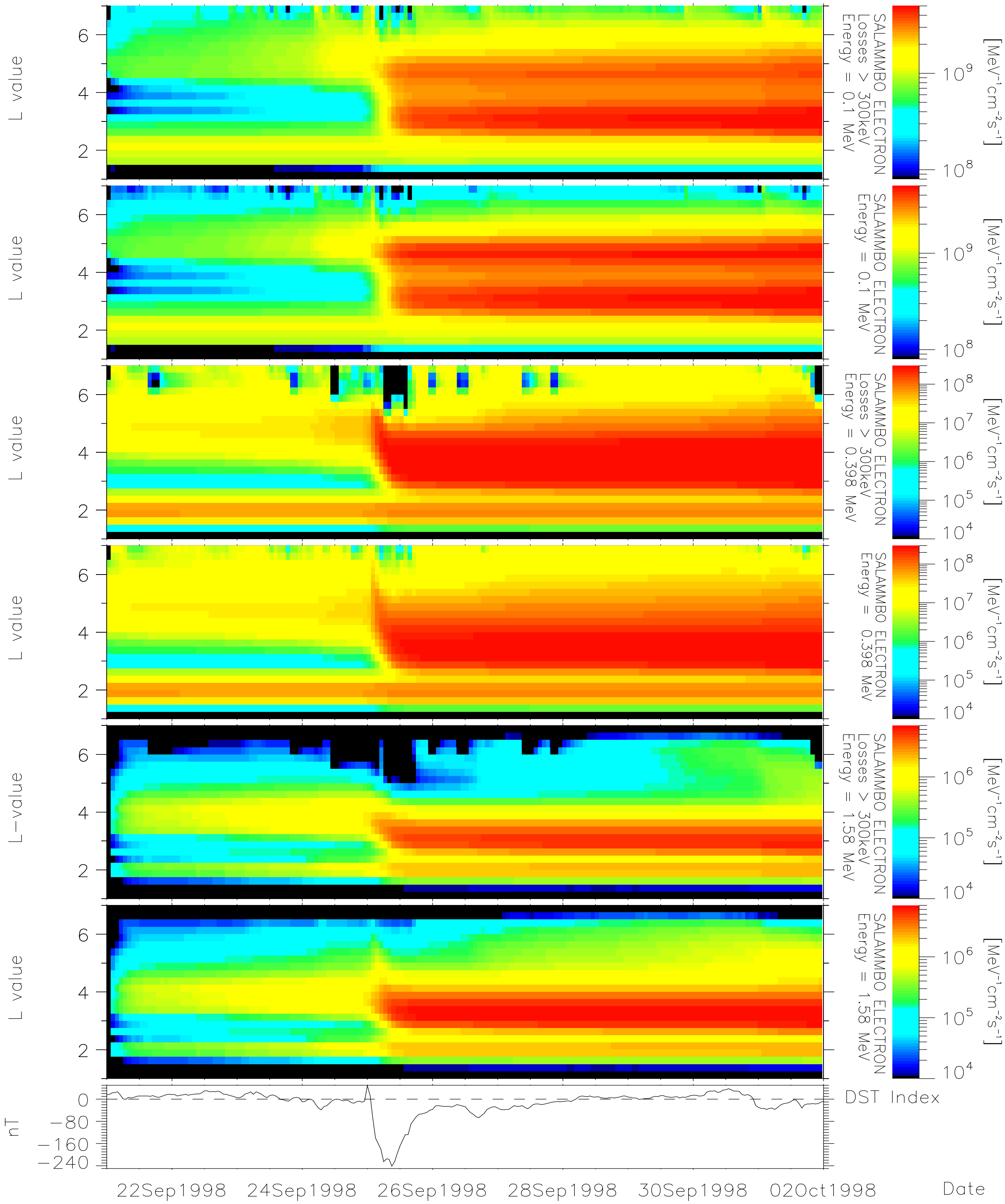
- Count levels must be well above background prior to steep gradient
- Count rates must fall by 0.5 decades in log space
- At least three energy channels need to observe the drop at the same time.



F3.

Results: Sept 1998 Storm
Loss modeling - no > 300keV

The Energetic Particle Team
at Los Alamos National Laboratory



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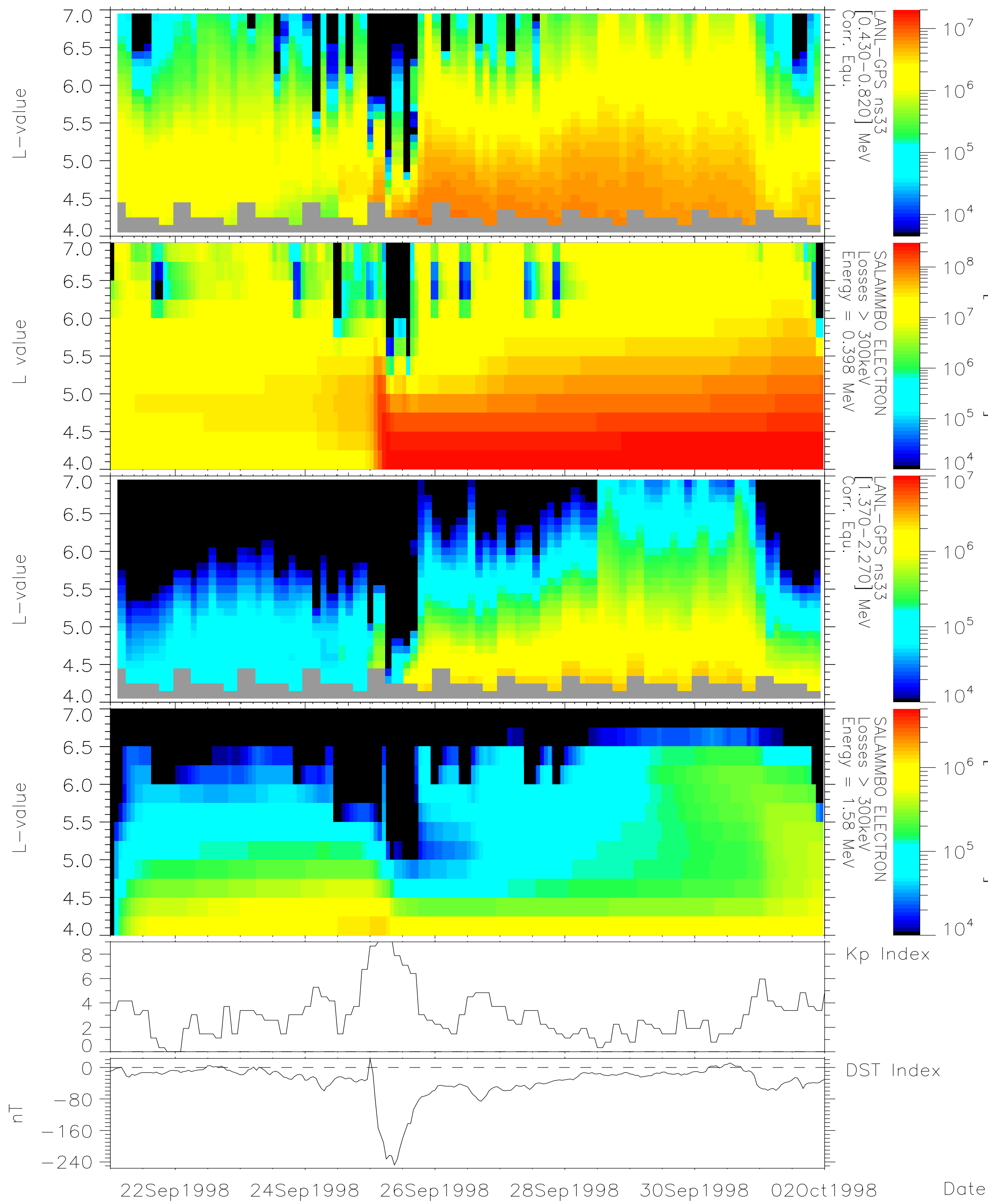
F4.

Results: Sept 1998 Storm
Loss GPS comparison



G. Summary

- Many of the processes described here are certain to be active at some time during some storms - the question that remains is, "Can we establish *which* process is the most important during any given storm?"
- Two classes of processes have emerged: those that rely on some kind of internal acceleration or recirculation mechanism and those that rely on increased radial transport alone.
- ULF waves seem to play a major role - in a statistical and theoretical sense. An agent for both increased diffusion and pitch angle diffusion.
- Needed are high fidelity multi-point measurements of both the magnetic field and the full particle distribution function.
- Inner magnetosphere constellation mission to solve all?

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